Aeroelastic Rotor Blade Dynamics for Helicopter Flight Mechanics Applications

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This paper elaborates on the theoretical development of a mathematical procedure, targeting the implementation of flexible rotor blade dynamics in helicopter flight mechanics applications. A Lagrangian approach is deployed in order to estimate the natural vibration characteristics of rotating blades with nonuniform radial distribution of mass, polar moment of inertia and flapwise/chordwise/torsional stiffness. Lagrange's equation of motion is applied to the kinematics of blade flap/lag bending and torsion. Modal characteristics obtained from Bernoulli–Euler beam and classical torsional vibration theory for an idealized non-rotating structure, are utilized as assumed deformation functions. Closed form integral expressions are incorporated for each degree of freedom, describing the generalized centrifugal forces and moments acting on the blade in terms of normal coordinates. A thorough discussion is offered on the treatment of three-dimensional elastic blade kinematics in the time domain. The motion derivatives are estimated based on a stable, 2^{nd} order accurate numerical differentiation scheme, previously used successfully in the context of time-accurate free-wake analysis. The developed rotor dynamics formulation is coupled with a finite-state induced flow model, an unsteady blade element aerodynamics model and steady-state fuselage potential flow model. An integrated simulation framework for helicopter rotor blade aeroelasticity analysis is therefore devised.

Results are presented in terms of predicted flap–lag–torsion natural frequencies and

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mode shapes for a full-scale hingeless and an articulated rotor blade model. Comparisons with non-linear finite element analysis are also included for validation purposes. The integrated rotor aeroelasticity analysis framework is deployed in order to investigate the in-flight trim controls and unsteady blade structural loads of both rotor systems analyzed. Extensive comparisons of predicted flapwise/chordwise blade bending and torsional moments with experimental data from flight tests are presented. The comparisons suggest very good and in some cases excellent accuracy levels in terms of predicted flap–lag–torsion natural frequencies, especially considering the method's simplicity and computational efficiency. Good structural loads predictive qualities are exhibited for a wide range of advance ratios. The simulations carried out suggest that, with regards to the hingeless rotor model, flapwise bending moment at the blade mid-span comprises predominantly harmonic content associated with the 2^{nd} and 3^{rd} elastic flap modes. Chordwise and torsional moments are shown to be mainly influenced by the contribution of the 1^{st} respective elastic modes